Quarterly Performance Report
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This status report is divided into the following six subsections:

I. ALGORITHM DEVELOPMENT

During the past quarter we have focused on researching and developing the precedence planner module of the assembly planning system. The precedence planner determines the relationships among parts based on geometric constraints.

Chen (1992) developed an algorithm to determine precedence relationships based on geometric constraints. However, with his algorithm, every part must be compared to every other part for each of the six assembly directions requiring 6*N! comparisons. This algorithm was developed for linear, monotone assemblies.

An assembly is linear if only one part is assembled at a time. An assembly is monotone if parts do not have to be placed into an intermediate position before reaching their goal position.

Our current work focuses on the development of a precedence planning algorithm that will solve for linear, non-linear, and non-monotone assemblies. To decrease the number of geometric detection operations from 6*N! we perform geometric detection on groups of parts or sub-assemblies. This reduces the number of operations to 6*N.

The precedence planner is composed of 3 modules: 1) linear disassembling module, 2) non-linear disassembling module, 3) and non-monotone disassembling module. The steps for this algorithm are briefly described below.

1. Linear module: Identify parts that do not require an intermediate step (montone) and that can be linearly disassembled from the assembled product. Identify an

obstacle set for each part.

2. Non-linear module: Identify the smallest sub-assemblies (more than one part) that can be disassembled from the parent assembly. Store these parts as non-linear operations.

3. Non-monotone module: Identify parts or subassemblies that require an intermediate position. The parts are stored as non-linear, non-monotone operations.

4. Constructing a disassembly tree: The nodes of the tree are the sub-assemblies. The branches of the tree indicate the assembly directions and operation. The operations are applied for the given direction and the tree is recurrently constructed by adding each sub-assembly node to the parent node.

The three modules have been implemented without a user or graphic interface. Research, development and testing of this algorithm will be continued during the next quarter.

Algorithms have been implemented for visualization of assembly sequences are discussed in the section Visualization Research.

II. VISUALIZATION RESEARCH

Automatic assembly sequence generation creates hundreds of sequences for one product. Completely automating assembly planning should reduce the number of questions asked of designers, however, complete automation has several drawbacks. Optimizing assembly sequences based on one or two criterion, like number of reorientations or minimizing tool changes, will not necessarily lead to superior assembly or the "best" assembly line. Engineers must consider soft constraints when planning an assembly. Soft constraints are constraints best inviolate --yet, if violated, do not harm the assembly sequence (Delchambre, 1992).

There should be a system eliminating possible sequences based on hard constraints while allowing the engineer to make decisions based on soft constraints. Therefore, the user needs simultaneous views of the many sequences --views that make sequence differences obvious. Obvious differences help the user delete unfeasible sequences within considered soft constraints.

Our visualization research has two directions: one uses graphic techniques to give the user a view of multiple feasible assembly sequences, the other examines techniques for comparing two sequences or examining one sequence in-depth.

Algorithm Development for Graphically Visualizing Multiple Assemblies

We are using a general 3-D graph developed by Kamada (1988) for our investigation. The graph's algorithm models each graph edge as the energy function of a spring and produces best results by minimizing the energy function. The natural length of the spring determines the maximal graph path of the as well as the size of the drawing area. This minimizing algorithm reduces edge crossings and provides symmetrical graphs.

Kamada's algorithm can be modified to deal with layered graphs. A layered graph is a graph where the vertical position of all nodes are quantized into fixed, predetermined values.

To optimize a layered graph, the Y values of each node are computed and fixed while minimizing. While this technique results in graphs with fewer edge crossings (i.e. a simpler graph), the algorithm does not provide satisfactory results with a large number of nodes.

To evaluate the algorithm, we used a liaison diagram created by Whitney and colleagues. In Whitney's diagram each assembly sequence is identified as one path from the top to the bottom node. Figure 1 is the optimized graph. Figure 2 is derived from Figure 1 by repositioning the nodes on each layer without changing rank or order. Improvements include fewer nodes among the layers. Edge crossings have been removed and it is easier to identify sequences that are similar. The total number of edge crossings in the original diagram by Whitney is 75, while the number of edge crossings in Figure 2 is 65. Further optimization, and optimization for more general cases, must be examined.

Each assembly sequence is determined by following a path from top to bottom in both Whitney's diagram and the graphs discussed above. It is difficult for a user to specify which sequence he or she wants to view with this visualization technique: a technique that will allow users to view multiple assembly sequences and choose one or several for comparison --without having to specify a path-- will help. If similar assembly sequences can be clustered together it will be easier for the user to determine differences among cluster subsets and similarities within cluster subsets. In an attempt to fulfill this need, we have implemented a dual graphical representation of all assembly sequences.

In contrast to the previous liaison diagrams, each node in a dual diagram represents an entire assembly sequence rather than a specific state in a sequence. Similar sequences can be shown through node closeness, and through coding techniques like node shape, size and color.

Producing clustering visualizations lets the user eliminate or keep certain assembly sequences based on soft constraints: the user will have the ability to compare assembly sequences between two separate clusters, or within a cluster.

Utilities allowing users to examine a sequence using both graphs (liaison and dual

graphs) have also been developed. Users can choose a node that represents an assembly sequence on the dual graph and the path will automatically be highlighted on the optimized liaison graph as illustrated in Figure 3. A node can also be chosen on the liaison graph and any assembly sequence used by that state will highlight a node on the dual graph (see Fig. 4).

Optimizing and evaluating these techniques from a human factors perspective still is needed because visualization with a large number of nodes is difficult. Research to determine criteria for clustering is in progress. The clustering technique is compatible with the way humans chunk information: information processing research indicates that the capacity of working memory is Miller's Magical Number 7 plus or minus 2 (Sanders and McCormick, 1993). Information should be presented in meaningful chunks and should be limited to 5 to 9 chunks of information.

Visualizing Several Assemblies

As the user narrows assembly choices, the ability to quickly compare two or three sequences is needed. If the user selects a node representing two assembly sequences in a cluster on the dual graph, visualizations should let the user quickly compare these two assemblies. Research into these visualization techniques include the design of 3-D spiral graphs that show an assembly sequence by including a step in the assembly on an orbit around a central base part (see figures 5-7). The farther the part is from the starting point, the farther the step is in the assembly. These graphs produce quick visualization of the possible reorientations an assembly would require and provides assembly directions. This technique may produce more relevant information than the typical illustration and numbering of each part specifying the assembly sequence (see Figure 8).

We are currently designing an experiment testing spiral graph technique effectiveness. Figures 5 through 7 show examples of possible configurations. This research will include investigation of 2-D versus 3-D stereoscope representations. Overlapping graphs to provide users with a quick view of different items will also be investigated.

Visualizing Single Assembly Sequences

When users want a quick, in-depth examination of one assembly sequence, we need to give them a visualization technique that allows sequence study. We are exploring several techniques for displaying a single assembly sequence. This visualization technique would be used after narrowing the number of feasible sequences to only a few and would allow the engineer to examine process details while keeping a global view of the whole assembly. By viewing a global diagram of the whole assembly sequence, designers can more easily see overall patterns and relationships between parts. This increases the speed that designers can find a feasible product or process because they can see the impact of design ideas on the overall project and anticipate problems they might have otherwise missed with a narrower focus (Newsom, Spillers, and Finger, 1989). Although this study will not explore comparing

several assembly sequences, it may be possible to modify the best technique from this study for comparison.

Three display techniques will be investigated in this study: 1) integrating display information; 2) using redundant spatial and verbal codes; 3) providing contextual information. Each of these techniques is describe in more detail below.

Integration: Although integrated displays have been studied for other applications, they have not been studied in the context of product assembly. Both interactive displays developed for assembly planning use separate windows to display the assembly diagram and the product picture.

Assembly diagrams in the literature use a series of nodes and arcs to represent assembly sequences. The assembly graph also uses words to describe how parts go together. The assembly could be portrayed using pictorial diagrams of the objects. Instead, researchers use symbolic, textual diagrams which force the user to operate at a higher level of thought than necessary. Although the displays contain a separate picture of the product in the lower corner of the screen, the pictures illustrate only a few nodes at a time. In the assembly graph display, the picture can also depict more than one assembly action. This requires the operator to use a higher level of thought to figure out which assembly action is illustrated by a given node.

The graph examined for this study also uses a series of nodes and arcs but, in addition, it provides a picture of the assembly in each node (illustrated in Figure 9). The resulting diagram will show a series of assembly action snapshots in the appropriate order. Integrating visual information with schematic diagrams eliminates the need to refer to separate pictures to understand the assembly sequence. It also eliminates confusion because each node represents only one assembly act. Integration should allow the operator to use more skill based behavior.

Pictures in nodes using the snapshot technique will be smaller than the pictures in the non-integrated displays so the entire assembly sequence can be seen. The smaller pictures may be hard to use for tasks that require more detailed view of the product. In order to see a larger image, the subjects will be able to expand any node to one of two larger sizes. The node will maintain it's relation to the other nodes using the fisheye technique (see Figure 10). The fisheye technique uses one of several distortion methods to enlarge a portion of the picture. The concept is similar to a wide angle, "fisheye" lens which shows close items in much greater detail than distant items (Furnas, 1986).

An integrated display is generally more cluttered than each of the individual displays. In some cases, the increased clutter overshadows the benefits of the integration technique. In order to determine if the integrated display improves performance, it will be compared to a format that uses separate windows.

Redundant verbal and spatial codes: Clutter can be reduced by eliminating verbal descriptions of assembly operations. Several experiments involving instructions for procedures and assemblies (Booher, 1975; Stone and Gluck, as cited in Wickens, 1984) indicate both codes may be necessary for optimum performance. However, in both studies the purpose of the instructions was teaching subjects to perform a particular procedure. This is different than the goal for assembly sequence displays, which is showing engineers what action took place. Engineers involved in assembly planning should be familiar with the product (or similar products) by the time they reach this stage of design (i.e., they should know how to assemble the parts).

Each node's purpose is showing what parts are being assembled --assuming the designers know how the parts fit together. In this case, every node communicates the same thing (assemble one part to another). It may be possible to use color coding instead of words to describe the assembly action. For example, the part being assembled can be highlighted with red since that part is of highest interest. The part into which it is placed can be shown in green. By using colored pictures to indicate what parts of interest, the information is presented in a totally spatial format. This reduces the level of thought (skill-based for picture and rule-based for color) and also allows the information to be parallel processed.

Although designers should be familiar with assembly operations, words may add clarity to the diagrams. Therefore, in addition to testing the picture-only display, a format with both pictures and words will be explored.

Context: The assembly graph display from the literature shows all product parts in the window though only a few are being assembled. This provides a context for the assembled parts and helps clarify the assembly process. Contextual information may help identify interference from parts other than those being assembled. It may also help the user anticipate future problems that could result from an assembly action.

Unfortunately, providing context requires showing every part in each of the snapshot assembly nodes. This results in clutter and may distract the user from the node's primary goal (i.e., communicating the assembly operation). Two contextual clutter solutions will be examined in this study: ghost-gray images and removing contextual information.

Non-assembled parts for all context displays will be shown in light grey for the first clutter-reduction (see Figure 9). The ghostlike images will still provide contextual information, but will indicate that the parts are not immediately important. The gray images will not be a study variable because they will be used in all context displays.

The second solution to clutter will be removing contextual information so that only the assembled parts are displayed (see Figure 11). The user will see the same parts in the nodes (like a picture at each stage of an actual assembly line). This may more closely match the user's mental model of the assembly than the abstract contextual pictures. However, the

engineer may confuse which parts are being displayed --especially if there are several similar parts. In order to reduce confusion, parts will always be shown in the same position in each node. An example: a part located in the upper right of an exploded view of the assembly will always appear in the upper right of the node, even if it is only one of two parts shown (in other words, the pictures will not be centered, but will maintain consistent positions in the node throughout the diagram).

Summary. Although two interactive assembly planning displays have been reported in the literature, both use abstract diagrams to communicate assembly sequences with a separate window to display the product. This format confuses the user. Our study proposes a snapshot technique that integrates schematic and pictorial information to simplify the display. Because integrated displays contain more clutter, several techniques may help simplify our displays.

One clutter reduction method removes verbal descriptions that accompany each node. Previous studies indicate users prefer redundant coding for procedural and assembly instructions; however, the instruction's purpose was communicating an action. The goal of the assembly sequence display, however is to show which action takes place.

The second clutter reduction method we will explore removes contextual information (parts not assembled) from the nodes. These models may more closely match the user's mental model of the assembly, but may provide less information for assembly analysis.

III. PROTOCOL ANALYSIS

We initially interviewed nine people from the Whirlpool Corporation: five design engineers, three designers, and one financial analyst. The interviewees came from a team developing Whirlpool's next generation built-in oven ranges (Vision II). Although confidentiality contracts limited the interviews, the interviews were helpful to our study.

Whirlpool agreed to help us because design for assembly and assembly planning are vital to their manufacturing process. In return for their help, Whirlpool asked for our results so future Whirlpool products could benefit from our research.

We interviewed the team about Vision II's five-phase development cycle:

1. marketing and benchmarking
2. product design
3. prototype hardware and testing
4. pilot production and testing
5. full production

Our researchers evaluated each of the five development phases and suggested improvements. We cannot discuss details because of the confidentiality contract, but our

recommendations for an improved cycle --a cycle reduced by 1 1/2 years and needing only four phases-- follows.

<u>**The Improved Cycle**</u>

PHASE I: marketing and benchmarking

Marketing examines customer wants and needs by using personal interviews, mail-in questionnaires, and phone interviews as evaluating tools. We recommended keeping customer information in a company-wide database that provides both word processing abilities (eases preparing reports) and statistical software (eases marketing evaluations). Information should be provided to corporate headquarters, styling design, engineering design, manufacturing engineering, quality engineering, and reliability engineering to ease improving customer satisfaction.

Benchmarking involves complete examination of a competitor's product. We recommended investigating the competing product's design engineering, manufacturing engineering, purchasing, and testing. Two of each examined product should be purchased: one should be disassembled to determine things like bill of materials and functional analysis relationships, the other should be thoroughly tested.

Disassembly gives ideas for improved material selection, design, production, and cost for future Whirlpool products. Improvements should be stored in 3D solid model graphic software system to provide rapid updating and accessibility.

Testing yields information on competitor's product strengths and weaknesses. This information gives Whirlpool an edge: new Whirlpool products can expand on strengths and remedy weaknesses of a competitor's product and thus improve corporate image and sales.

PHASE II: product design

The second development phase is product design. We recommended Whirlpool perform a human factors analysis and obtain a product artist's conceptual designs. Conceptual designs should be drawn with or linked to a CAD system so they are available to all engineers during the design process. Wide design access will improve communication among design product artists, design engineers and process engineers. Design considerations should include quality, reliability, performance, fit, assembly, ease of manufacture, and cost.

A <u>PERT</u> chart is useful during phase II: it states when, where, and who performs what tasks. All team members should have access to the PERT chart to keep tasks on schedule and team members informed of new developments.

PHASE III: prototype and plant preparation

In our recommended third phase the detailer, using a 3D assembly solid model of the product, designs parts for production and for prototype hardware. This stage is critical because it determines who builds the prototype hardware, and how and where it is built. We recommended manufacturing prototype hardware in the same plant that will manufacture full production hardware to increase product development efficiency: manufacturing and partnership suppliers quickly learn of problems and possible solutions.

A prototype should be tested to see not only if it meets government standards but also if design improvements work. It is best to have standards far higher than the government's to remain competitive: today's consumers are quality conscious.

PHASE IV: full production

The final stage of the improved development cycle is full scale production. Before full production begins, all detail drawings should be updated based on prototype test results. Pro-Engineer should be used for changes because any detail drawing changes automatically change assembly drawings. Manufacturing then installs new machinery and permanent tools, and what is traditionally pilot production becomes full production.

Notes, Observations, and Future Plans

No further interviews with Whirlpool are planned because we need to interview process engineers and the Whirlpool manufacturing plant is located in Mississippi. It is, however, essential to our study to understand the manufacturing plant environment, so we contacted a local company, BF Goodrich, which has both an engineering department and a manufacturing plant at the same facility.

Goodrich agreed to provide process engineers and two products for our protocol analysis. The protocol analysis should gather information about stages of assembly planning, assembly constraints, application of relevant assembly constraints, and strategies used for assembly planning. We will first conduct a pilot study to prepare experimental procedures and to understand process engineers' activities prior to the experiment. For the pilot, a new product currently being developed by B.F. Goodrich will be used as the testing stimuli. The process engineers will be asked to discuss the development of an assembly sequence for a given product design.

The experiment will follow the pilot study. For the experiment, discontinued products will be used as testing stimuli so the engineers will develop their own assembly sequence rather than remember sequences for products currently produced that they may be familiar with.

The number of parts for each product in the controlled experiment is between 25 and

50 because of time constraints. Video equipment will be used to collect protocol data. We have decided to supply the subjects in the study with a drawing of a completed model and with individual drawings of each part comprising the model. The part drawings will be numbered and the assembly order of these parts will be recorded by hard copy. However, to discover the thought process engineers use, there is a continuous need to prompt them to think aloud during the task. The peer process engineer --also supplied by BF Goodrich-- will be the prompter. Three advantages to peer participation are: 1) it creates a more natural environment for the subject; 2) peer feedback on the subject's assembly decision helps ensure work quality; 3) peer participation opens the possibility of exploring collaboration issues beyond the main research focus. We expect to conduct both the pilot study and the actual experiment in October.

The data from the protocol analysis will provide information about knowledge needed at different assembly planning stages. Function allocation between the computer system and the user can be determined. Problem areas in assembly planning can be identified, and visualization research can point to possible solutions.

IV. PUBLICATIONS and ABSTRACTS SUBMITTED

Conference Submissions:

Automatic Generation of Assembly Plans: Human Factors Considerations: Submitted by Jennie J. Gallimore to the First Automation Technology and Human Performance Conference, Washington D.C., April 7-8, 1994

Human Factors Considerations in the Development of an Assembly Planning System: Submitted by Jennie J. Gallimore to the Specialized Symposium on Human Factors in Design for Manufacturing, Canada, August, 1994

Publications Submitted:

Gallimore, J. J., Chen, C.L. P., Ye, N., Chen, J. Research and Development Issues for an Assembly Planning System. Submitted to *International Journal of Human Factors in Manufacturing.*

Other

Dr. Gallimore has been invited to chair a special session at the Third Industrial Engineering Research Conference May 18 and 19, 1994 on Human Factors in Manufacturing.

Dr. Gallimore has been invited to participate in the Ergonomics in Manufacturing Workshop November 18 and 19, 1993 sponsored by the National Science Foundation and the University to Cincinnati. The purpose of this workshop is to explore the role of human

factors and ergonomics in manufacturing.

V. CONTACT WITH INDUSTRY AND GOVERNMENT

We are working with Whirlpool and B.F. Goodrich in Dayton, OH.

VI. GOALS FOR THE NEXT PERIOD (September 30 - December 29, 1993)

1. Completion of data collection and analysis of the protocol experiment. An article based on the results will be submitted for publication.

2. Refinement of hard and soft constraints for the assembly modelling component of the system.

3. Optimizing the current graph drawing algorithm in terms of edge crossings.

4. Investigation of the effectiveness of the dual graph representation.

5. Completion of the data collection and analysis of the single assembly representation experiment.

6. Programming for experimentation of the spiral graphing technique.

7. Determine how to interface with Pro-Engineering using the Pro-Develop Module.

8. Research, development, and testing of the precedence planner algorithm.

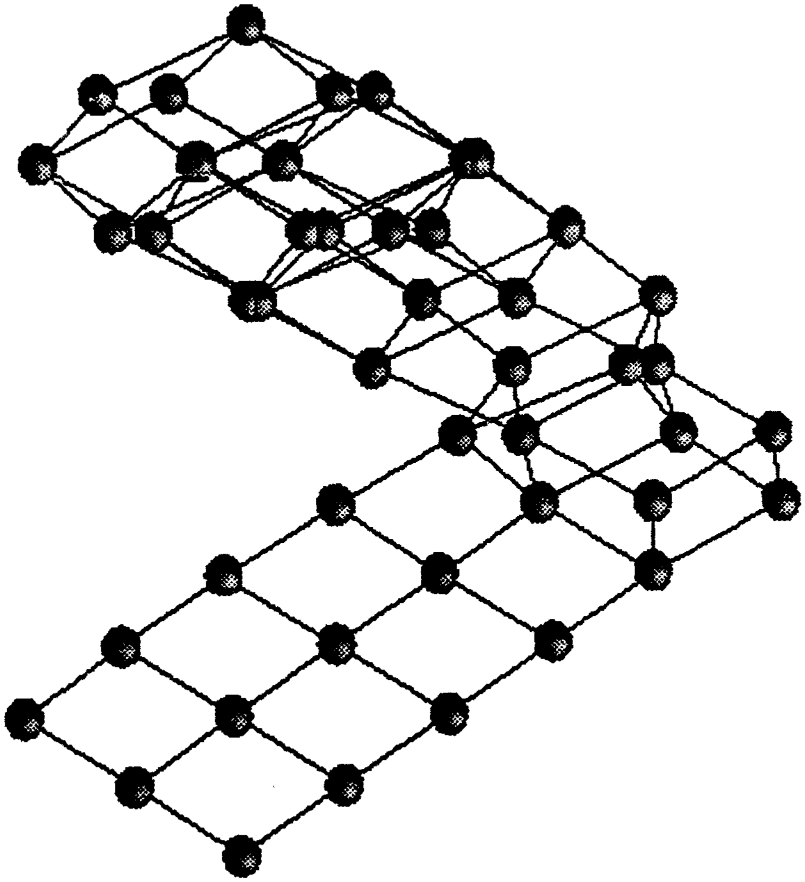


Figure 1. Optimized layered graph.

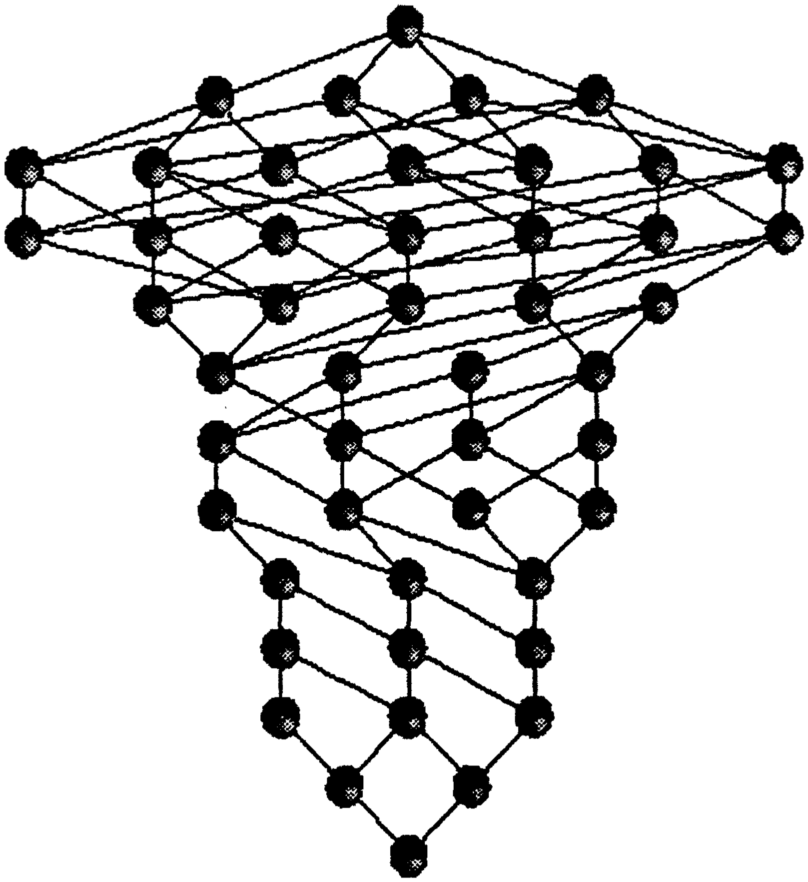
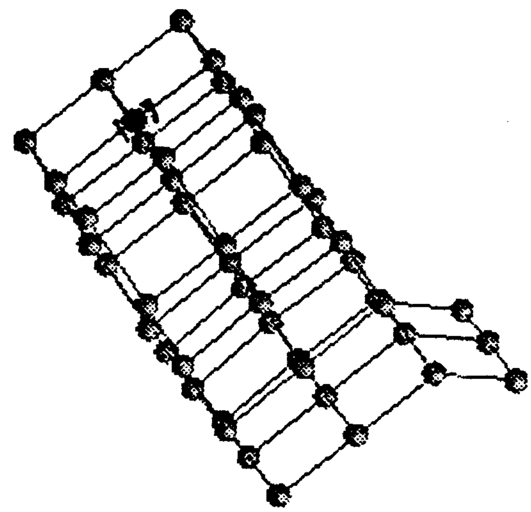


Figure 2. Optimized layered graph after repositioning nodes.



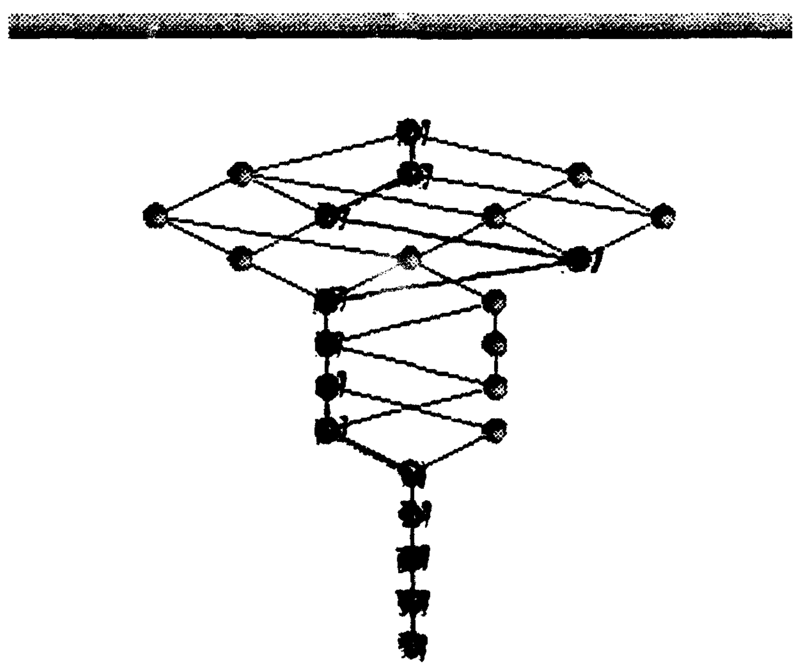


Figure 3. A chosen node representing an assembly sequence on the dual graph (a) automatically highlights the assembly path on the optimized liaison graph (b)

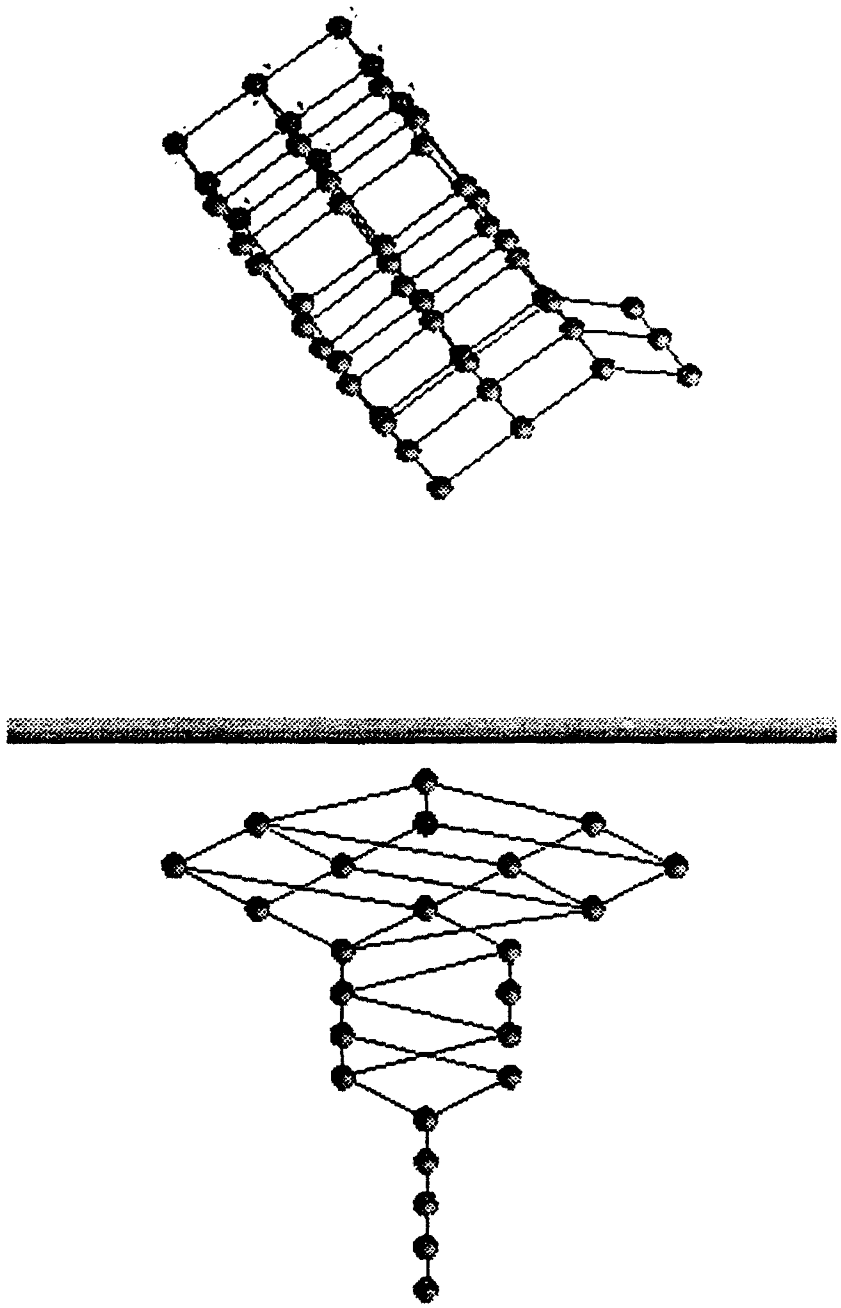


Figure 4. A node is chosen on the liaison graph (b) and any assembly sequence using that state is highlighted on the dual graph (a).

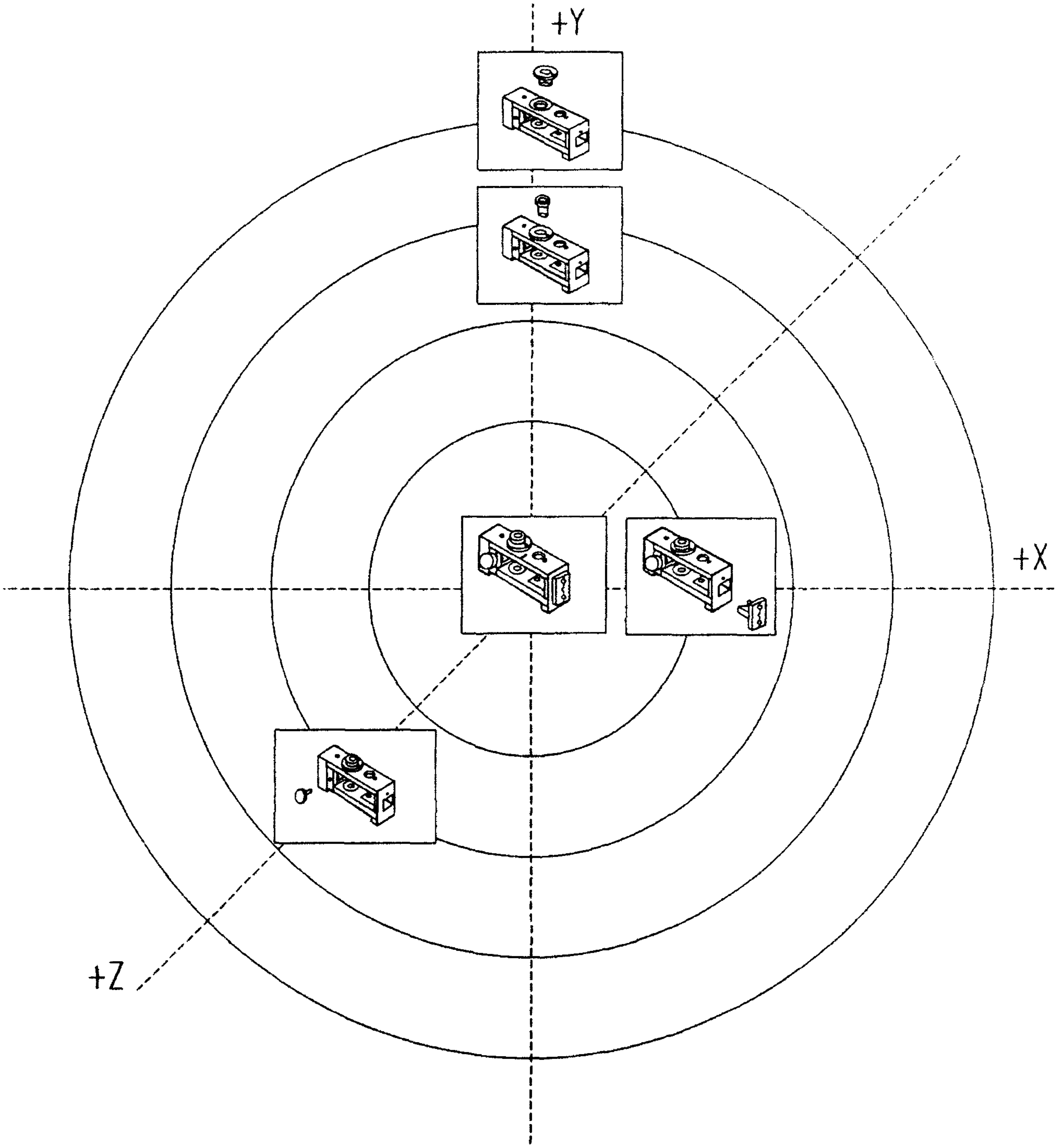


Figure 5. Direction: outside to inside; graphical representation using subassemblies

The user begins the assembly sequence at the outer-most circle and moves to the center, one level at a time. Each assembly step is represented as a single part being connected to a subassembly. The completed part is represented at the center of the graph.

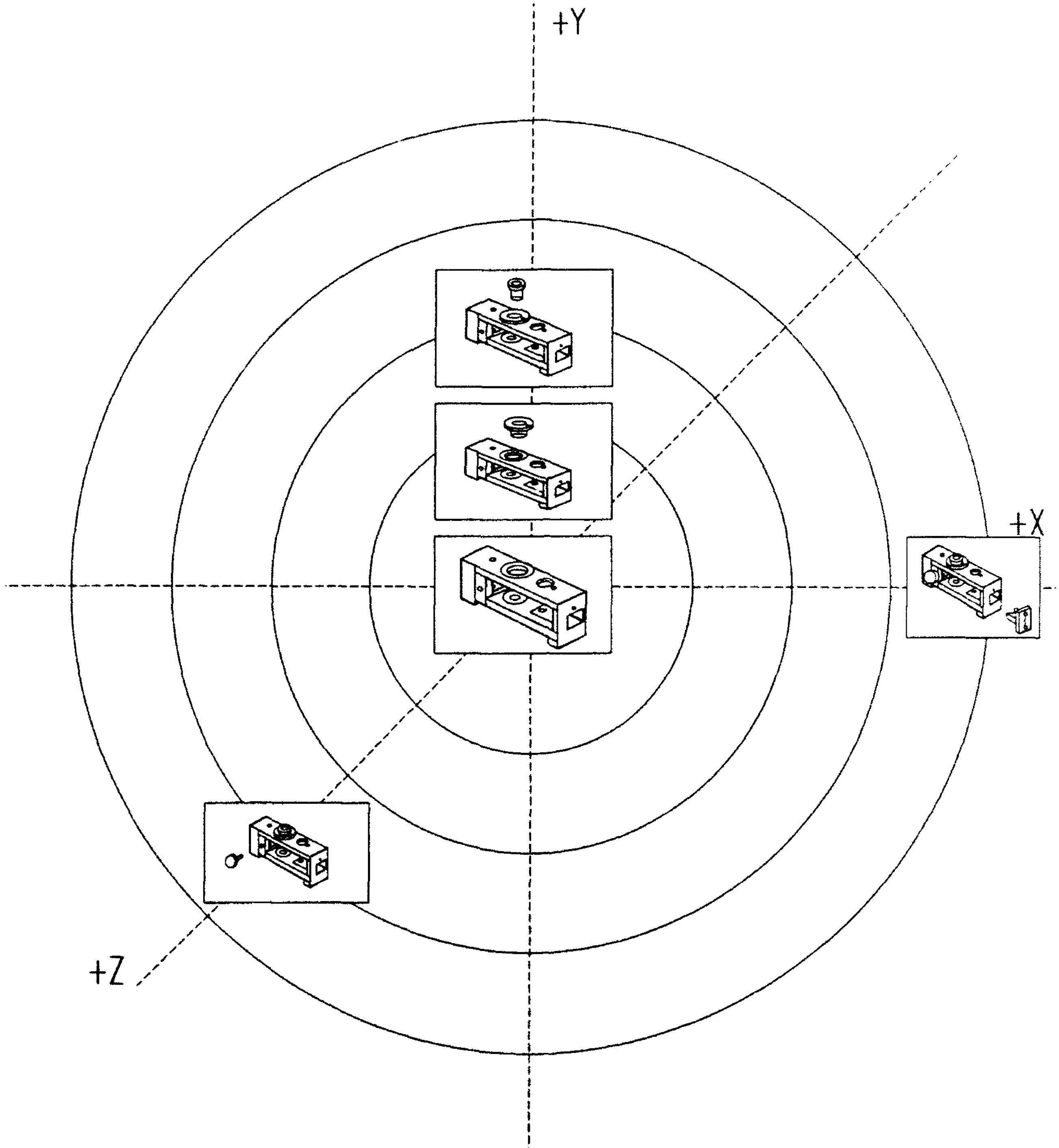


Figure 6. Direction: inside to outside; graphical representation using subassemblies

The user begins the assembly sequence at the center of the graph with the base part and moves to the outer-most level. Each assembly step is a part being connected to a subassembly (the final part being added at the outer most level).

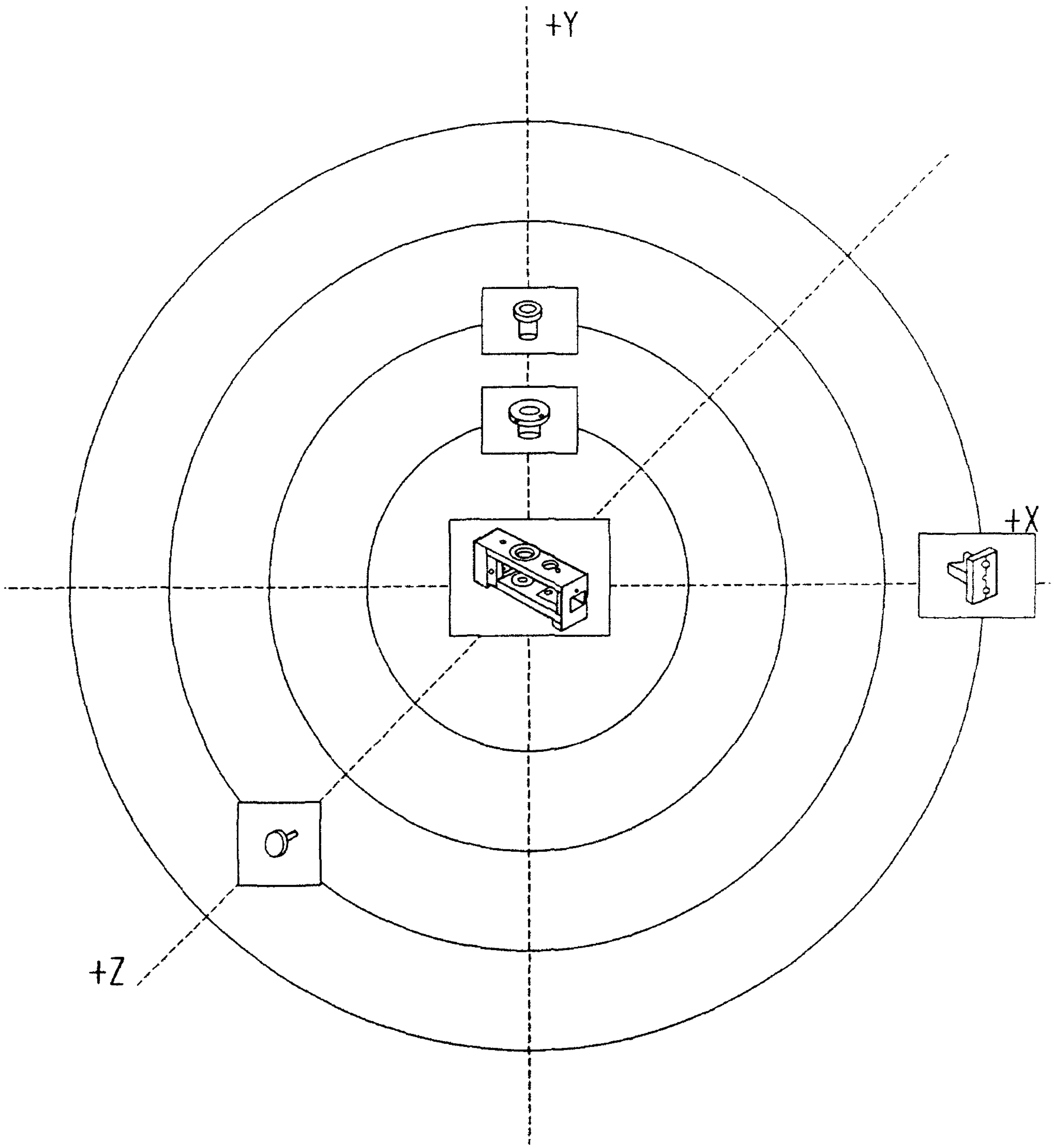


Figure 7. Direction: inside to outside; graphical representation using single parts

The user begins the assembly sequence at the center of the graph with the base part and moves to the outer most level. Each assembly step represents a single part that attaches to the base part. There is no representation of the final assembly -- or the subassemblies that proceed it.

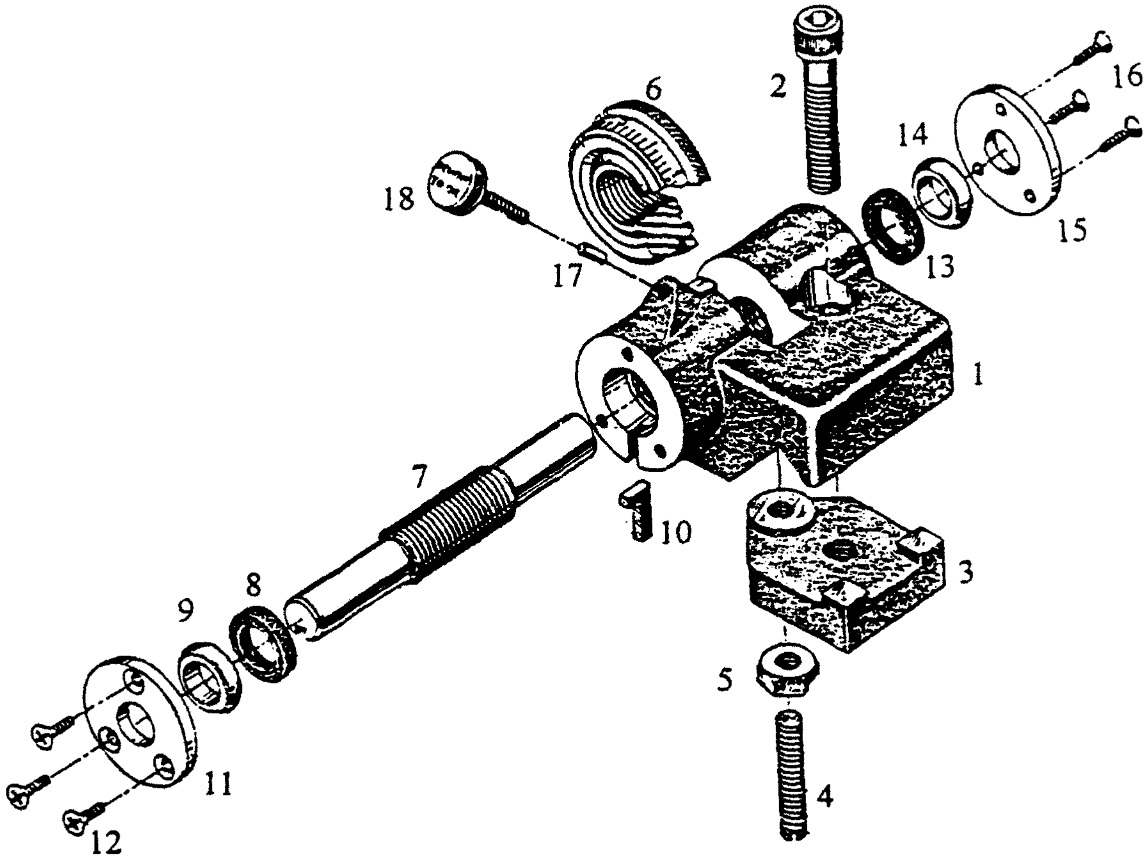


Figure 8. Graphical representation of assembly with part sequence numbers.

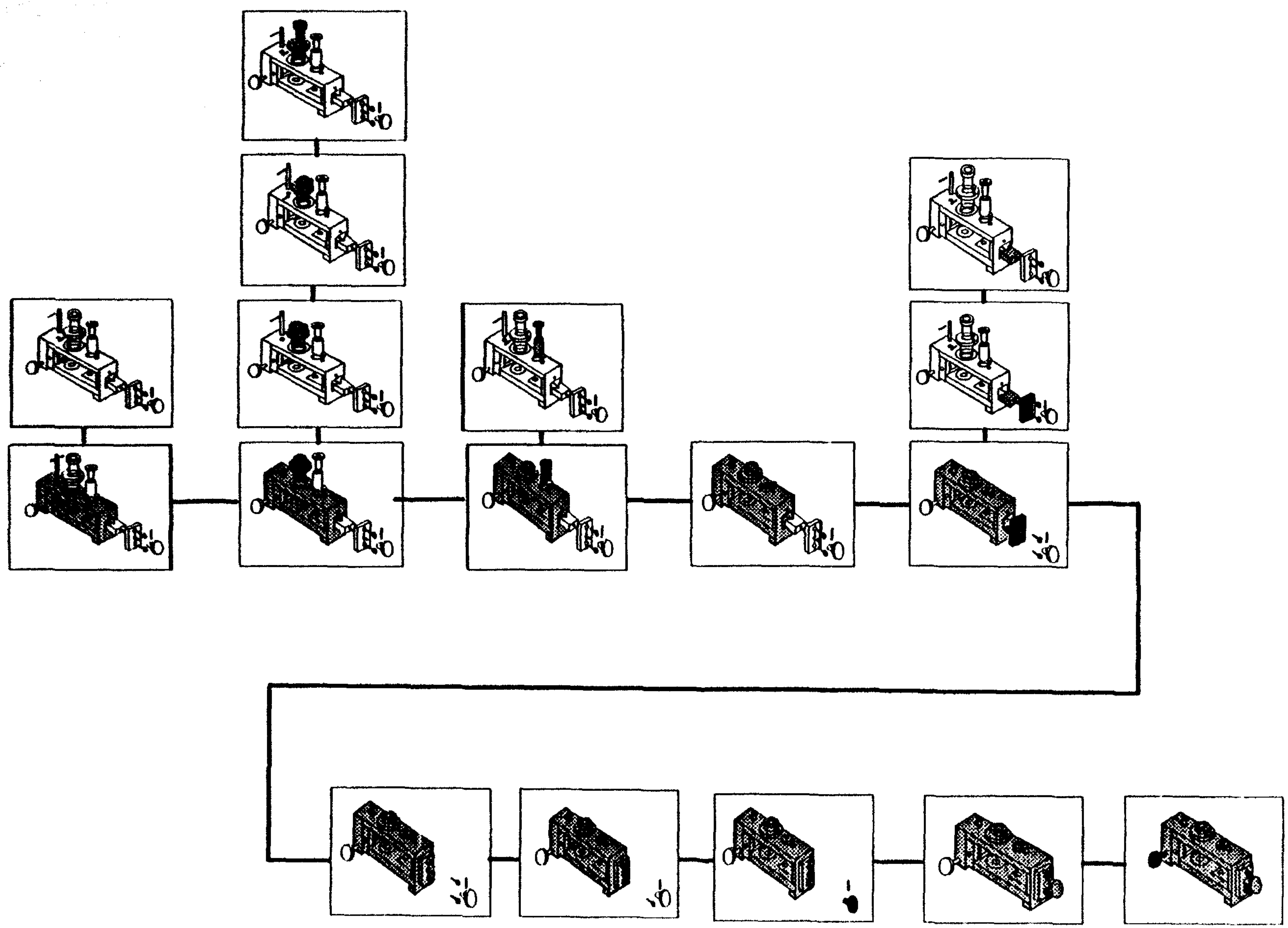


Figure 9: Snapshot technique for visualizing a single assembly sequence

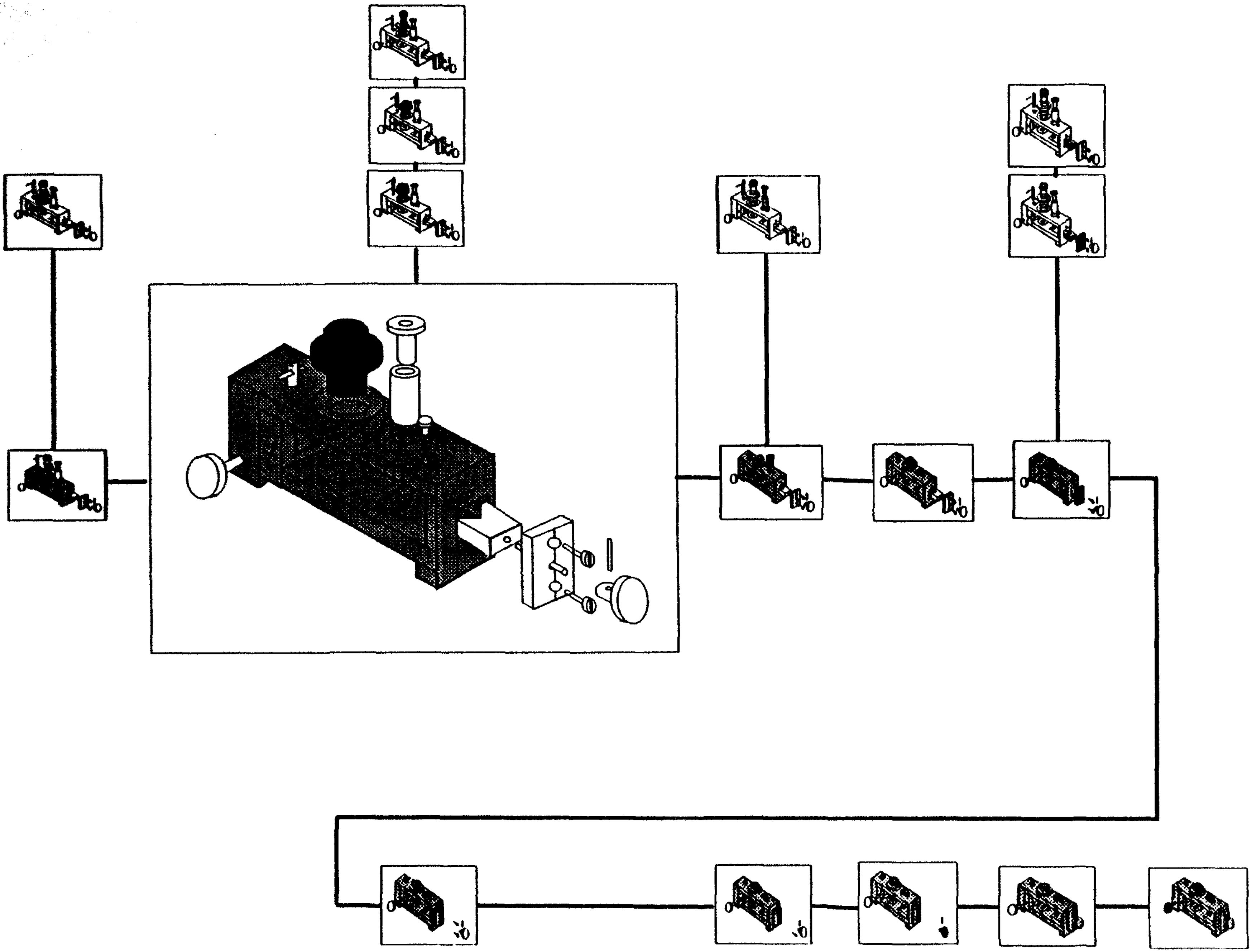


Figure 10: Fisheye technique

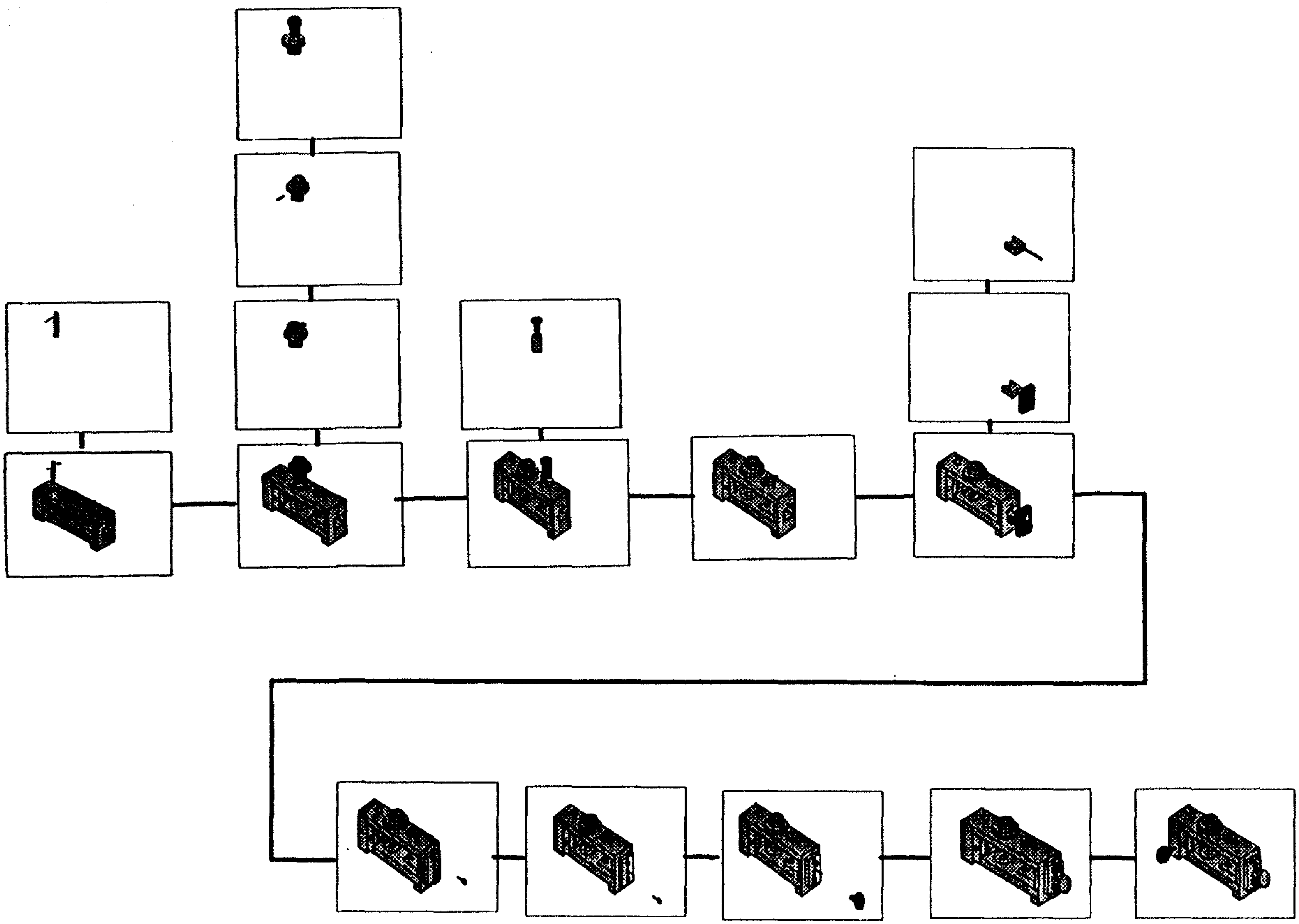


Figure 11: Snapshot technique with context removed